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Optical and digital holographic interferometry applied in art conservation structural diagnosis

REVIEW

V. Tornari

Applied Optical & Digital Holography Laboratory, Laser Applications Division, Institute of Electronic Structure and Laser, Foundation for Research and Technology-Hellas, Vassilika Vouton, Voutes, 71 110 Heraklion-Crete, Greece

corresponding author:
vivitor@iesl.forth.gr

Abstract

Holography and holography-related interferometry have emerged as new tools for conservation researchers and practitioners, and are used to visualize structural faults and mechanical disconti-nuities in the bulk of an artwork. These may be an important fac-tor of deterioration and can be a consequence of various degra-dation processes, caused by environmental parameters, trans-portation, handling, and various conservation and restoration actions. Holographic analysis is based on studies of interference patterns created by controlled surface reflection of diffused laser beams. Since no sample removal or surface preparation is nec-essary to visualise faults and defects the techniques are regard-ed as non-destructive and non-contact. This brief review pro-vides a comprehensive introduction to the basic physical princi-ples of operation with a description of some case studies.

1. Introduction

Alteration of structural and mechanical properties of artworks is an important factor of deterioration causing their slow but steady disinte-gration. Through the use of lasers and the principles of holography and holographic interferometry a novel tool to visualize the invisible disintegration has been introduced to the conservation community.

The holographic technology is not based on light penetration but on reflection of diffused laser beams from the artwork surface. Holography and related techniques involved in structural diagnosis do not require any sample removal or surface preparation and are safe for use on varnishes and pigments. In this context, the techniques can be classified as non-destructive, non-contact and non-invasive.

The methodology to visualize the defects of interest is based on dif-ferential displacement provoked in time by two slightly different posi-tions of the reflecting surface of interest. The displacement results in a relative optical path change of the reflected beams, which can be optically or digitally converted to a patterned signal. The obtained dark and bright patterning is the "encoded" response of the examined

artwork and indicates its conservation state.

The range of applications of laser interference is remarkable. The invention of holographic interferometry is of major significance as it serves as a scientific and engineering tool in many fields of application for which it is uniquely suited.[1-3] The development of holographic interferometry has also influenced the development of several closely related measurement techniques based on the use of laser light including speckle photography and interferometry, holographic phototelasticity, projected fringe techniques, holographic contour generation, holographic techniques incorporating television systems, phase shifting and wavefront shearing.[4-7] The theory, practice and application of these techniques are very similar and often complementary to holographic interferometry, which may serve as reference to the field of structural diagnosis in art conservation in which applications are in development.

In the conservation field, holographic interferometry was first applied to detect subsurface damage in the Donatello statue in Venice and in a fifteenth-century panel painting.[8,9] This work introduced the optical coherent interference measurement as a novel and alternative information source in **analysis of structural condition**. Subsurface structural information in terms of visually assessable (qualitatively and quantitatively) systems of **fringe patterns** can be produced by complex surfaces and three-dimensional shapes. Small or inborn discontinuities in the bulk and their effect on the mechanical instability of the artwork construction can be optically and digitally obtained. The regions of defect become revealed as isolated discontinuous regions in contrast to overall continuous distribution of the interference fringe system. This allows for accurate representation at one-to-one scale, and subsequent restoration.

2. Physical principles

The ability of holographic techniques to visualize subsurface anomalies and their effects on artefact structural condition without any penetrating irradiation is founded on the unique property of holography to generate a record of phase distribution of the reflected beams.

Phase is a fundamental property of light, along with amplitude, polarization, and wavelength. However, due to the high frequencies of light ($\sim 10^{14}$ Hz), it is a property which can be captured only by using two identical laser beams, coherent in time and space. Due to minor phase changes of the order of a fraction of the wavelength, the overlapping of the two laser beams produces interference effects ($\phi_0 - \phi_1 = \Delta\phi$). This forms the fundamental difference between holographic and other imaging techniques, e.g photography. Photography

records the amplitude distribution of reflected light, averaged in time. On the other hand, holography records all light information: amplitude and phase (hence its name holo - all and graphy - record). The holographic result is a high-density record of object information with distinctive optical properties such as paraxial viewing at full vertical and horizontal parallax and object image in three-dimensions at one-to-one scale. If the recording procedure is repeated after a slight alteration of the object e.g following a slight surface temperature increase, its phase characteristics are also slightly altered and affect the reflected phase-carrying beam. When the two records are reconstructed and spatially superimposed all minor phase alterations are visualized in the form of intensity distributions - the well-known bright and dark interference fringes.

The patterned result of holographic interferometry visualizes the structural condition. All subsurface anomalies or mechanically stressed areas show a distinct response. Each non-uniform response is visualized in locally distinct generation of interference fringes. Therefore, the number of localized fringe patterns found in one holographic interferogram is a measure of structural faults in an object.

The mathematical description of interference fringe formation is based on wave optics equations for linearly polarized monochromatic light. The expression for any sinusoidal plane wave can be written in the following form

$$\Xi = \xi_0 \sin \omega t,$$

where $\omega = 2\pi/T$ is the angular frequency and ωt is the value, defining Ξ for any t at position 0. Holography is a technique reproducing light waves and the signal of interest is the wave since it carries the information on the object. Additionally, a second beam is recorded simultaneously to produce the interference effect. This beam is called the reference beam since it is the original beam from the laser source without any induced modulation. Thus, for a light wave propagating at z direction to fall in the recording plane $z = 0$, the wave reflected by the object at t_1 takes the form:

$$\Xi_{1object}(x,y) = \xi_0(x,y)\sin(\omega t + \phi_1),$$

and the same object at a later instant t_2:

$$\Xi_{1object}(x,y) = \xi_0(x,y)\sin(\omega t + \phi_1),$$

The resulting wave superposition gives the total amplitude

$$\Xi_{total} = \Xi_1 + \Xi_2 = 2\xi_0 \sin(\omega t + \frac{\phi_1+\phi_2}{2})\cos(\frac{\phi_1-\phi_2}{2}).$$

This expression represents an intensity variation which varies between the maximum value

$$I + I_2 + 2\sqrt{I_1 + I_2}$$

and the minimum value

$$I + I_2 + 2\sqrt{I_1 - I_2},$$

known as the fringe pattern of bright and dark fringes. Dark fringes are contours of constant phase difference of odd-integer multiples of π and bright fringes of even-integer multiples of π.

In relation to interferometry, slight deformations affect primarily the phase, ϕ. Thus, the parameter of interest - the phase shift - is expressed in terms of intensity fluctuations of Ξ with $\Delta\phi = 2\pi N = N\lambda/2$, where N is an integer expressing the relation of the phase shift to the physical quantity inducing the optical path alteration and thus the object displacement. In the particular case of a one-dimensional deformation, the relation is applied as it is. Otherwise, three dimensional measurements of N from three viewing angles are required for accuracy.

The experimental procedure for double exposure recording begins by capturing the initial object state (Table 1). Then, an excitation is applied. For artwork examination, thermal perturbation is well suited, as it provokes a variety of responses allowing better visualization of defects. An indicative table of duration of such excitation is shown in Table 2, and results in a temperature difference among the initial and the later states of the examined artwork. The temperature difference can be explored starting from low to higher values by changing the duration of excitation. Hygroscopic materials respond faster even at very low values of ΔT. After the excitation had been applied, a second exposure of equal duration as the initial one is recorded on the same photosensitive medium. The holographic interferogram is thus recorded and the chemical development of the film follows.[10]

The basic arrangement for holographic interferometry is shown in Figure 1. The laser source L emits

Step	Experimental procedure
1	Align the artwork to reflect a diffuse laser beam to the photosensitive medium where a reference beam is also directed at an angle Θ.
2	Use a white card or a photometer to balance the intensity of the interfering beams.
3	Block the beams off and allow the system to settle at resting positions.
4	Unblock for the 1st exposure allowing the necessary time corresponding to the total brightness required (unbalanced ratios or low brightness require high exposure times).
5	Turn on the thermal lamp or any suitable device to induce a temporary displacement.
6	Unblock the beams for a 2nd exposure of an equal duration as in the 1st exposure.

Table 1: A typical recording procedure.

Duration of excitation (s)	Initial temperature T_o (°C) (at artwork surface)	Final temperature T_1 (°C) (at artwork surface)	$\Delta T = T_1 - T_o$
1	24.9	25.7	0.8
2	25.2	26.4	1.2
4	25.6	27.7	2.1
5	26.2	28.6	2.4
7	27.4	30.8	3.4
9	26.2	30.0	3.8
12	26.5	31.3	4.8

Table 2: Indicative table of induced thermal effects, e.g on cellulose-based constructions, using a 150 W IR lamp.
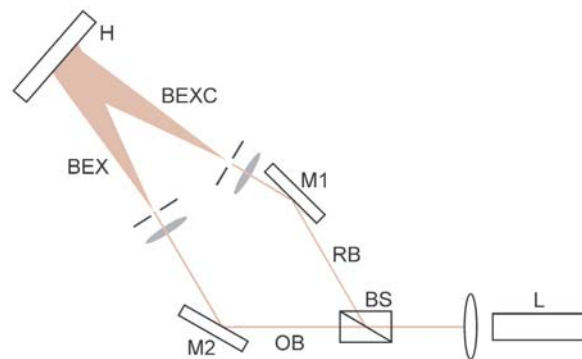

Figure1: Schematic optical arrangement for a holographic recording. The object beam is transmitted through the object placed at a distance (BEX) in the OB path. For opaque objects, the beam is reflected from the object to the H plane where it is superimposed with the beam in the RB path.

a linearly polarized plane wave of wavelength λ. The beam is split by the beam splitter (BS) and as a result, two beams emerge. The reference beam (RB) is expanded by an optical system for beam expansion which usually consists of a diverging and collimating lens (BEXC) to diverge the beam at a desired divergence depending on object size and laser power. A spatial filter (SF) is often used to clean off higher spatial frequencies due to diffraction noise. Keeping good quality optics free from dust minimises the need to align a SF. The mirror M1 directs the beam towards the photosensitive medium where the hologram H is to be formed. The object beam OB is expanded by another diverging lens (BEX) or spatial filter (SF) and is directed by mirror M2 to illuminate the object and then to coincide in time and space with the reference beam (RB) in order to form an invisible interference pattern, i.e. the hologram which is then recorded on the medium H.

An object can be put in the OB beam path, either in a reflected or transmitted mode. In either case the beam paths OB and RB should be equal in length. The procedure to form a hologram can be repeated twice, after a thermal emission device, e.g. a hot-air gun or an IR lamp, affects the object surface to produce displacement. The thermal effect on the surface can be measured directly on the artwork surface and the operator can control

Figure 2: Left: a photograph of Saint Sebastian (attr. to Raphael, National Gallery of Athens, Greece); right: its holographic interferogram.

the final temperature to induce a pre-specified temperature difference. The produced total displacement is very small, i.e. of the order of few microns to few tenths of microns but are satisfactory to reveal hidden discontinuities in the bulk of the object since slight differences can be measured at the measurement scale of multiples of half-wavelengths.

Especially for holographic interferometry experiments with beams of high divergence a stable table isolated of all vibration and magnetic holders for optical and mechanical components in order to isolate any extraneous motion which may interact with clear displacement of the object are better suited. If a pulsed laser is used for illumination, this requirement is less strict, but the operator should foresee and isolate any extraneous rigid body motion between the pulses. Attention is necessary to keep the ratio of intensities of the reference and object beams ideally at 1:1 or maximally 1:10. The intensities are measured at the recording plane. There are no strict directions for implementing an IR lamp; it is instead far more important to control the thermal difference through thermometer readings since a high ΔT may result in irresolvable fringe densities.

For double-exposure holographic interferometry, the same optical arrangement can be used as for recording a single hologram.
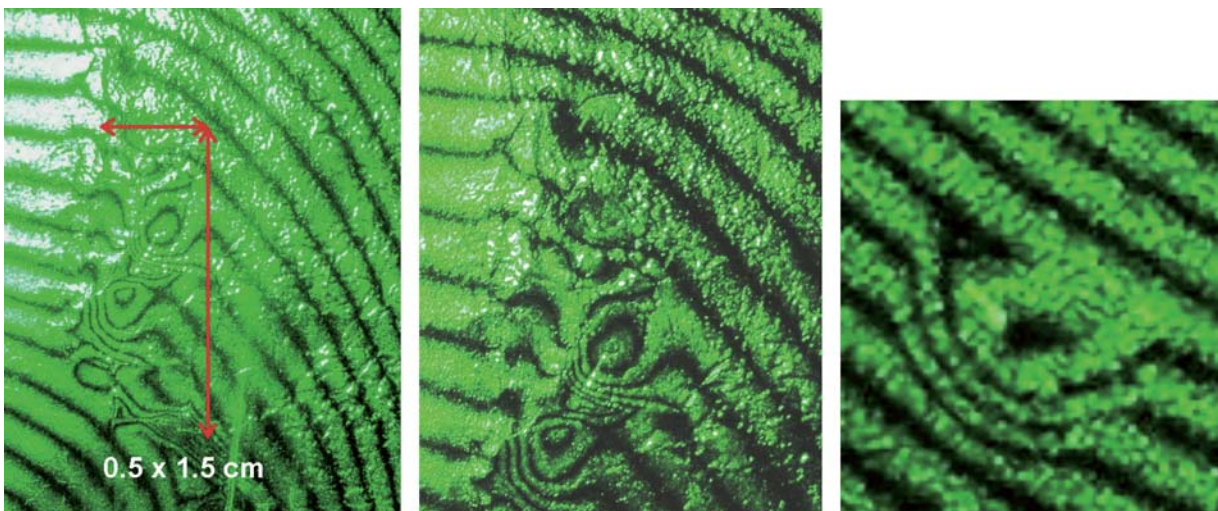

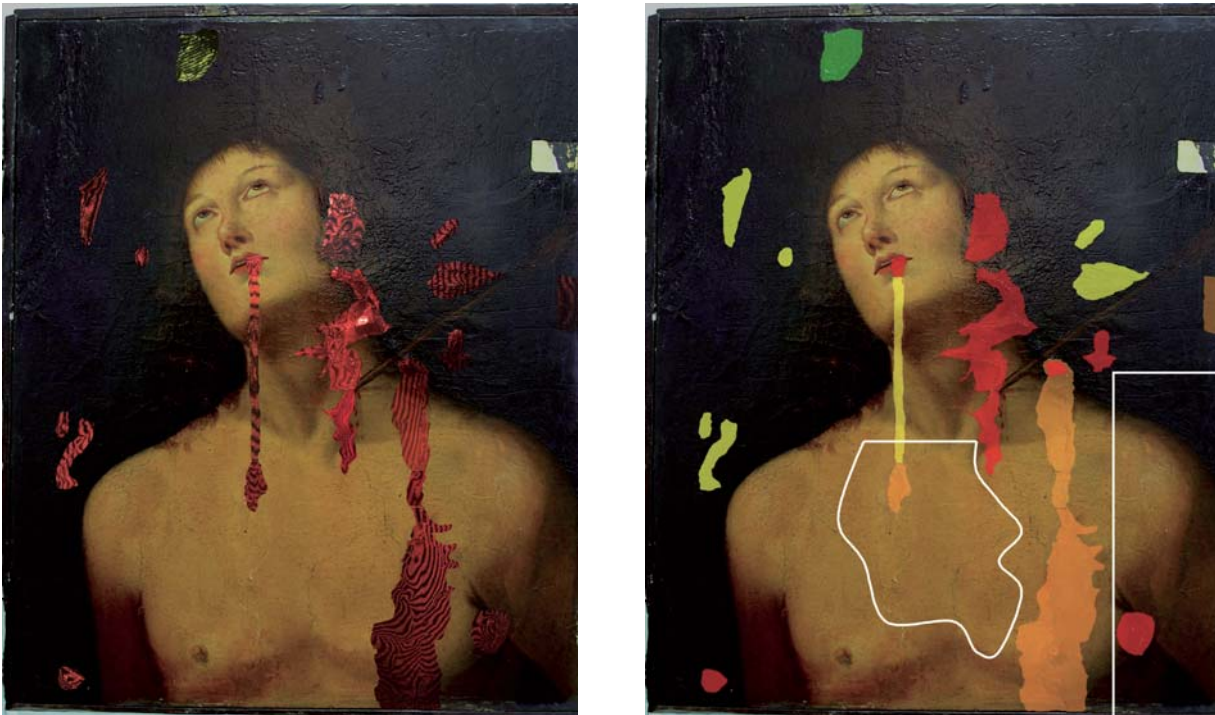Figure 3: Defects as seen in the interferogram in Figure 2, right.

Figure 4: Images of the Saint Sebastian painting as obtained with holographic interferometry. Left: a high-fidelity analysis of defects, right: The risk map of the painting with areas of inhomogeneous varnish and material indicated by shaded areas.

3. Case Studies

3.1 Optical Holographic Interferometry

Holographic interferometry is well-known and has been used in a number of applications in art conservation research.[3, 11-17] Its ability to reveal structural defects is of primary interest. In this section, an analysis of defects on a panel painting is used to demonstrate the potential of the technique as a structural diagnosis tool: in Figure 2 (left) the painting of Saint Sebastian attributed to Rafael is shown (National Gallery of Athens, Greece).

In the interferogram (Figure 2, right) we show the overall interference fringe distribution produced by the painting surface displacement, i.e. the concentric bright and dark zones distributed all over the surface constituting the fringe pattern. Note that it is locally interrupted by smaller fringe patterns which visualise various structural discontinuities. By zooming in these discontinuities and extracting them as in the interferograms shown in Figure 3, we can locate and isolate them so that only defects are depicted as in Figure 4.

After the defects have been isolated only the areas of the painting with anomalies are visualized, a risk map of endangered areas, as shown in Figure 4, is obtained. An X-ray photograph may visualize the presence of nails and holes. Other defects, not visible in an X-ray image are additionally revealed in the interferograms, due to detachments between layers (see Fig. 3, left), propagation of cracks or wormholes (see detail Fig. 3, centre, a crack

among patterns of detachments) etc.

A colour map can also be produced representing localised fringe values estimated from the overall measurements of painting displacement. Green is used to depict areas of displacement almost equal to the overall displacement, while red represents areas which are most strong displaced.

3.2 Digital speckle holographic interferometry

Holographic interferometry can be also used for in-situ applications due to the more recent development of speckle holographic interferometry recording techniques.[18] For the digital techniques, the recording medium is a charge-coupled device (CCD) instead of a film or a crystal as the photosensitive medium. Special algorithms and opto-electronic devices for image acquisition and processing are used. In Table 3, some characteristic features of a typical CCD sensor used for speckle interferometry are shown.

Sensor size - WxH (mm)	10.2 x 8.3
Pixels - WxH	1392 x 1040
Pixel Size – WxH (µm)	6.45 x 6.45

Table 3: Typical CCD sensor features.

The possibility of employing speckle interferometry in artworks structural diagnosis was explored soon after the development of computerised fringe acquisition and processing. An increased interest for art conservation applications followed the first preliminary on-field result of the technique.[18] The
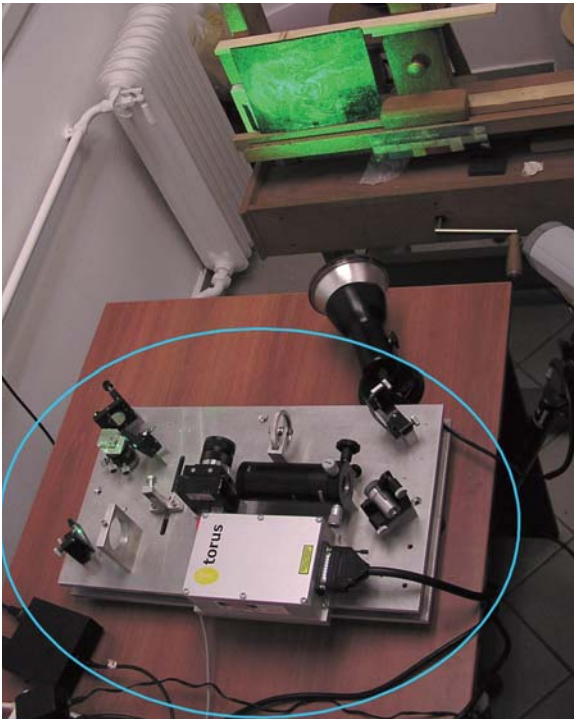
Figure 5: Left: transportable digital speckle holographic interferometric (DSHI) system (Benaki Museum, Athens, conservation lab), right: pulsed DSHI for in-situ applications (St Johns co-Cathedral, Malta).

interference recording geometry follows the principles as well as the working procedure of double exposure holographic interferometry.

For in-situ applications under the framework of the EC-funded project LASERACT, a speckle holographic interferometric system was developed using a custom-made pulsed laser as the source. The system allows investigation of monuments in extreme conditions.[19]

In Figure 5, a transportable prototype is shown during examination of an El Greco painting at the Benaki museum, Athens, Greece, and the system in its final configuration during a measurement campaign in Malta.

The developed system, used both in continuos-wave and pulsed mode of exposure, has been successfully used to reveal defects, both in laboratory conditions and in-situ. An example of numerically reconstructed detachment from a tomb in Constanza, Romania, is shown in Figure 6.

Surface defects on the multilayered wall painting became apparent as a discontinuity of the fringe system (Figure 6, right). The capability of such systems to be used remotely may vary, but given that coherent laser sources are used for this application, the distance can be at least 0.5 m from the target of interest, with a recording procedure lasting from a few seconds to a few minutes at each position. Beam divergence is also variable, but

Figure 6: A study of defect detection in wall paintings in a crypt in Constanza, Romania. Right: an example of the detected detachment.

even with low-energy lasers it can be minimally 30 cm, due to high sensitivity of the recording media (both films and CCDs). Thus, one can record the whole surface of endangered wall paintings to reveal detached regions without the need for scaffolding and without having to carry heavy instrumentation.

4. Conclusions

The development of lasers and of techniques of holographic interferometry has recently enabled the development of new tools and techniques for cultural heritage preservation and protection. The need for accurate, repeatable and reliable analysis of structural condition opened the field to optical and digital laser metrological methods. The present expansion of holography allows us to perform investigations not only in laboratories, but also in situ. The adaptability of the measurement geometry and procedures is very promising and may lead to standard protocols for applications of laser metrology tools in art diagnostics.

Hence, laser structural diagnosis achievable by full-field holographic and speckle pattern techniques provide ideal features to bridge the gap between conventional and modern diagnostic procedures and faster, safer and accurate structural data collection. The non-contact character of investigation ideally suits the needs to investigate and monitor artworks, especially regarding structural imperfections and dimensional changes in routine manner. The ongoing research in the field has delivered routine inspection procedures, transportable systems, software friendliness which facilitate non-expert operation. These advances can be regarded as a very important recent achievement.

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